FIFTH INTERIM TOPICAL REPORT

on

A STUDY OF THE MECHANICS OF
CLOSED-DIE FORGING

CALCULATION OF GEOMETRICAL PARAMETERS IN
DESIGNING THE FORGING PROCESS FOR
AXISYMMETRIC SHAPES

to

ARMY MATERIAL AND MECHANICS RESEARCH CENTER

October 15, 1969

20060110137

by

T. Altan, D. E. Nichols, H. J. Henning,
and A. M. Sabroff

Contract DAAG46-68-C-0111

BATTELLE MEMORIAL INSTITUTE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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FOREWORD

This topical report, "Calculation of Geometrical Parameters in Designing the Forging Process for Axisymmetric Shapes", covers the analytical work performed under Contract No. DAAG46-68-C-0111 by Battelle Memorial Institute, Columbus, Ohio, from April 30, 1969, to July 15, 1969.

This work was administered under the technical direction of Mr. Dennis Green of the Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172.

This program was carried out under the supervision of Mr. A. M. Sabroff, Chief of the Metalworking Division, and Mr. H. J. Henning, Associate Chief of the Metalworking Division. Dr. T. Altan, Senior Scientist, is the principal investigator.

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ABSTRACT

A computer program in FORTRAN language is developed for calculating geometrical parameters for axisymmetric forgings. Using the dimensions and the angles given in the engineering drawing of the forging, the program calculates the forging volume and weight. The shape-difficulty factor may prove useful in process design, for cost estimating, and for assisting engineers to make decisions about feasibility and difficulty in manufacturing. Empirical equations suggested by German and Soviet workers are used for calculating the flash dimensions and the flash weight. The computer program is applied to various forgings, and theoretical results are found to agree with actual experimental data. The developed computer program is now available to interested forging companies. It could be used for a systematic analysis of existing forging data, for making cost estimates after incorporating in-house cost factors, or for designing axisymmetric forgings with minimum additional effort.

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CALCULATION OF GEOMETRICAL PARAMETERS IN DESIGNING THE FORGING PROCESS FOR AXISYMMETRIC SHAPES

by

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INTRODUCTION

The design of a forging process involves the calculation or the prediction of

(1) Forging volume and weight
(2) Number of blocker shapes to be used, if any
(3) Flash geometry, flash width, and flash thickness
(4) Flash weight and scale losses
(5) Total forging weight, including scale and flash losses.

The second interim topical report, "Methods for Estimating Flash-Gap Dimensions and Flash Weight in Closed-Die Steel Forging", described a shape-difficulty factor for axisymmetric forgings first introduced by Soviet workers.[1]* At this time, this factor includes only the geometrical shape of the forging but excludes the effect of forging material, die wear, and forging tolerances. The shape-difficulty factor appears to be useful in predicting the difficulty involved in forging a part and in calculating the flash dimensions and flash weight by using statistically derived empirical formulas. These formulas and the derivation of the shape-difficulty factor were given in the second topical report, and they are summarized in Appendix A. In the present work, the derivation and practical use of a FORTRAN computer program is described. This program calculates, from the dimensions given in the engineering drawing of a particular forging, the following variables:

(1) Volume of actual forging, excluding flash and scale losses
(2) Shape-difficulty factor
(3) Flash width and flash thickness
(4) Weight of the flash and scale losses
(5) Total forging weight, including scale and flash losses
(6) Plane area of forging, including flash.

The computer program is written for axisymmetric steel forgings forged from a cylindrical billet. However, it can be extended easily to analyze intermediate blocker forgings necessary for forging complicated axisymmetric shapes. Practical shop experience will be necessary to develop the shape-difficulty factor into a characteristic quantity that indicates, for a given material, the number of necessary blocking operations and the fabrication cost associated with a specific forging shape.

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*References to work described in three papers by Russian authors have been discussed in the second interim report.

In order to calculate the volume of a forging using the dimensions in the engineering drawing of the forging, the forging is divided into various small components for which the volumes can be calculated by means of well-established formulas. This procedure is carried out in practice in most companies by using formulas, charts, or nomograms. Complete computerization of this procedure is proposed, at least for the axisymmetric forgings. With the time-sharing computer terminals available today, even a small company that does not have a computer can acquire a computer terminal at minimal expense to carry out the calculations described in this report.

In order to use this computer program, the user is not required to know the details of the mathematics or of the programming involved. He must, however, know how to prepare the input data for the program. However, the details of the geometrical derivations and of the computer program are given in this report so that those interested in research and development can use this information for future expansion of the present approach.

BASIC VOLUME COMPONENTS OF AN AXISYMMETRIC FORGING

The practical method for determining the total volume of a forging consists in dividing the forging into simple basic geometrical shapes and then calculating and adding the volumes of all components. Figure 1 illustrates the volume components of a simple axisymmetric forging. Using well-known formulas, the volumes are easily calculated. Tables are available for determining the volumes of the small-volume components described by the arc and the edges of the corners or fillets of the forging. This procedure can be computerized along with the determination of the shape-difficulty factor. The shape-difficulty factor described in the second interim topical report and in Appendix A is evaluated by determining the following variables for an axisymmetric forging:[1]

(1) The perimeter of the axial cross-sectional surface, P

(2) The surface area of the axial cross-sectional surface, S

(3) The radial distance from the axis to the center of gravity of half of the cross section, R_G.

For determining the forging and the flash weights, it is also necessary to calculate the volume of the forging.

For this purpose, the forging is divided into basic volume components that are analyzed below. Throughout this analysis, the computerization of all calculations is emphasized.

Cylinder

The half cross section of a cylinder is shown in Figure 2a. The radii R_i and R_{i-1} describing the cylinder are subscripted in order to facilitate the adaptation of derived formulas for computer programming. These dimensions are obtained from the engineering drawings of the forging.
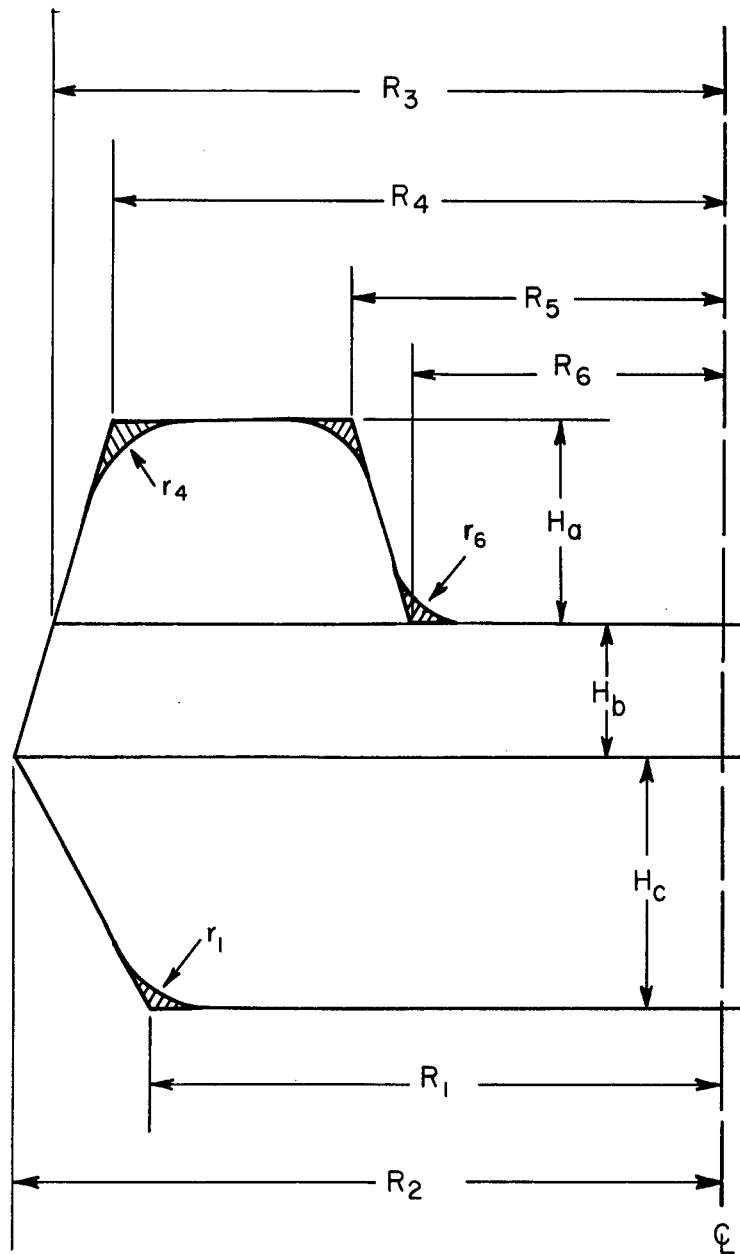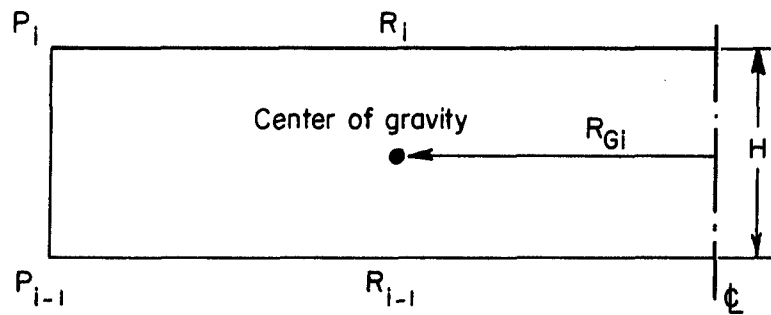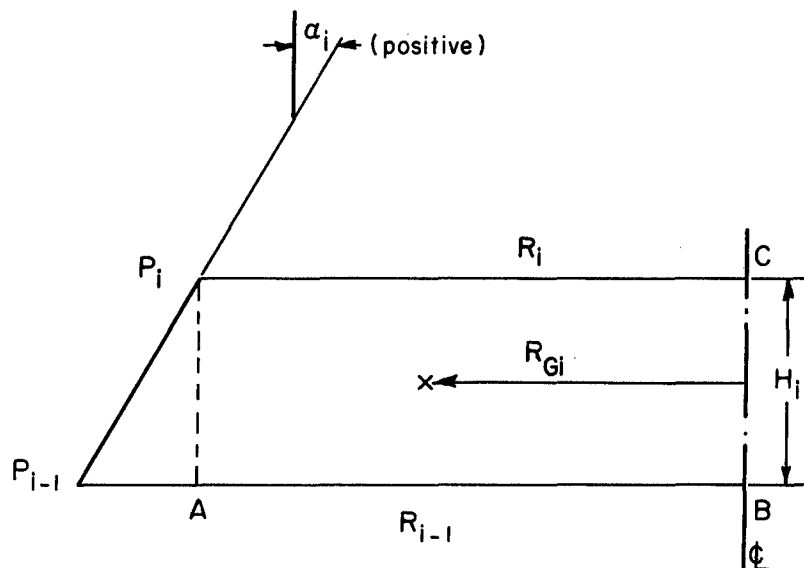
FIGURE 1. DIVISION OF A FORGING INTO SIMPLE GEOMETRICAL
VOLUME COMPONENTS

a. Cylinder Half Cross Section

b. Truncated Cone Above the Parting Line

FIGURE 2. SYMBOLS USED IN DESCRIBING THE GEOMETRY OF THE HALF CROSS SECTION OF A CYLINDER AND OF A TRUNCATED CONE

5

Using the symbols of Figure 2a, the following variables are easily calculated:

The segment of the perimeter, i.e., the distance between the points P_i and P_{i-1}:

$$\overline{P_i \, P_{i-1}} = H \tag{1}$$

The surface area of the half cross section:

$$S_i = R_i H \tag{2}$$

The volume of the volume component:

$$V_i = \pi R_i^2 H \tag{3}$$

The radial distance from the center of gravity of the half cross section:

$$R_{Gi} = R_i/2 \quad . \tag{4}$$

For a half cross section of a cylinder as shown in Figure 2a, Equations (1), (2), (3), and (4) give the segment of the perimeter, the surface area, the volume, and the radius of center of gravity, respectively. These four quantities are necessary to calculate the shape-difficulty factor and the volume of the entire forging.

Truncated Cone

The half cross section of a truncated cone is shown in Figure 2b. The angle of taper, α_i, measured with respect to the centerline, is considered positive if the taper is above the parting line of the forging.

As in case of the cylinder, the geometrical variables for the half cross section of the truncated cone seen in Figure 2b, are calculated as follows:

The segment of the perimeter:

$$\overline{P_i \, P_{i-1}} = \left| H_i/\cos \alpha_i \right| = \left| (R_i - R_{i-1})/\sin \alpha_i \right| \tag{5}$$

The surface area:

$$S_i = (R_i + R_{i-1}) H_i/2 \tag{6}$$

The volume:

$$V_i = \pi(R_i^2 + R_{i-1}^2 + R_i R_{i-1}) H/3 \quad . \tag{7}$$

The radial distance from the center of gravity of the half cross section seen in Figure 2b is obtained by considering the triangle $P_i P_{i-1} A$ and the rectangle $P_i ABC$ as the components of the half cross section. The following relation holds:

R_{Gi} x total surface area = surface of triangle x R_{GT} of the triangle + surface of rectangle x R_{GR} of rectangle,

where

R_{Gi} = center of gravity radius for the half cross section

R_{GT} = center of gravity radius for the triangle

R_{GR} = center of gravity radius for the rectangle.

Thus,

$$R_{Gi} S_i = \left[R_i + \frac{(R_{i-1} - R_i)}{3} \right] \frac{(R_{i-1} - R_i) H}{2} + \frac{R_i R_i H}{2} \quad . \tag{8}$$

Using the value of the surface S_i from Equation (6), Equation (8) is solved to give:

$$R_{Gi} = \frac{(R_i^2 + R_i R_{i-1} + R_{i-1}^2)}{3(R_i + R_{i-1})} \quad . \tag{9}$$

For a half cross section of a truncated cone as seen in Figure 2b, Equations (5), (6), (7), and (9) give the segment of the perimeter, the surface area, the volume, and the radius of center of gravity, respectively.

Truncated Cone With Fillet

The half cross section of a volume component, described by two radii, R_i and R_{i-1}, and by fillet radius r_i, is illustrated in Figure 3a for positive draft angles (draft angles are positive for the part of the forging above the parting line) and in Figure 3b for the negative draft angles. Following Figure 3a, the values which are given in the engineering drawing are:

(1) Edge radius, R

(2) Fillet radius, r_i

(3) Angles α_i and α_{i-2}.

In some cases, the value of the edge radius, R, is not explicitly given in the engineering drawing but has to be calculated from other given dimensions. These secondary calculations are incorporated in the final computer program.

From Figure 3a, the following quantities, which are also valid for the conditions of Figure 3b, are calculated by using the geometrical relations:

$$\text{Angle } \beta = \left| \alpha_{i-2} - \alpha_i \right| \tag{10}$$
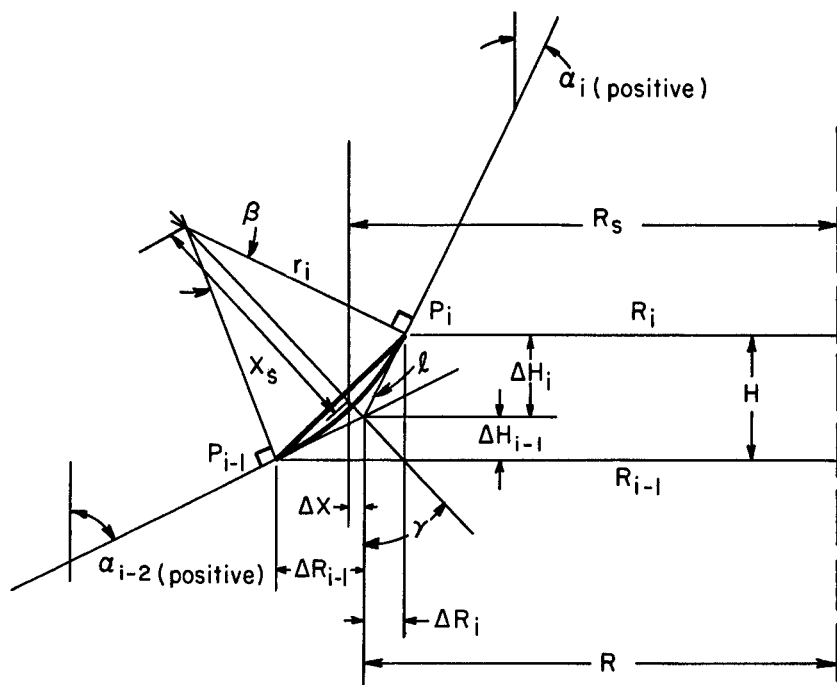
a. Positive Draft Angles α_i and α_{i-2} (Above the Parting Line)
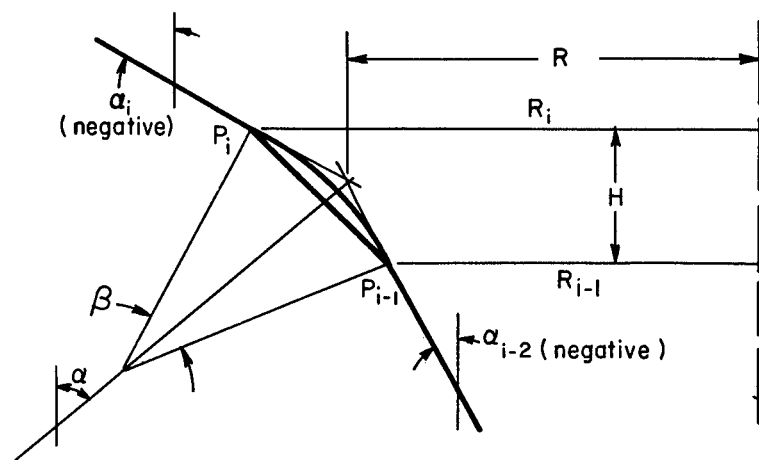
b. Negative Draft Angles α_i and α_{i-2} (Below the Parting Line)

FIGURE 3. SYMBOLS USED IN DESCRIBING THE GEOMETRY OF A
A TRUNCATED CONE WITH CONCAVE FILLET

and, using

$$\ell = r_i \tan (\beta/2) \tag{11}$$

$$\Delta K_i = \ell \sin \alpha_i \tag{12}$$

$$\Delta H_i = \ell \cos \alpha_i \tag{13}$$

$$\Delta R_{i-1} = \ell \sin \alpha_{i-2} \tag{14}$$

$$\Delta H_{i-1} = \ell \cos \alpha_{i-2} \tag{15}$$

Using Equation (12), the radius for the point P_i is

$$R_i = R - \Delta R_i \quad . \tag{16}$$

Using Equation (14), the radius for the point P_{i-1} is

$$R_{i-1} = R + \Delta R_{i-1} \quad . \tag{17}$$

The height, H, of the volume component considered is

$$H = \Delta H_i + \Delta H_{i-1} \quad , \tag{18}$$

where H_i and H_{i-1} are given by Equations (13) and (15), respectively.

The surface area of the circular segment defined by the straight line $\overline{P_i P_{i-1}}$ and by the arc $P_i P_{i-1}$ is

$$A = \frac{r_i^2}{2} (\beta - \sin \beta) \quad , \tag{19}$$

where the angle, β, is given by Equation (10).

The distance between the center of the arc and the center of gravity of the circular segment is

$$x_s = \frac{2}{3} \frac{r_i^3 \sin^3 \beta/2}{A} \quad . \tag{20}$$

The distance, Δx, as seen in Figure 3a, is

$$\Delta x = \left(\frac{r_i}{\cos \beta/2} - x_s \right) \sin \gamma \quad , \tag{21}$$

where

$$\text{angle } \gamma = \beta/2 + \frac{\pi}{2} - \left| \alpha_{i-2} \right| \text{ for } \alpha_{i-2} > 0 \text{ (Figure 2a)} \tag{22a}$$

$$\gamma = \frac{\pi}{2} - \beta/2 - \left| \alpha_{i-2} \right| \text{ for } \alpha_{i-2} < 0 \text{ (Figure 2b)} \quad . \tag{22b}$$

The radius for the center of gravity of the circular segment defined by the arc P_iP_{i-1} and by the line $\overline{P_iP_{i-1}}$ is given by

$$R_s = R + \Delta x \ . \tag{23}$$

The quantities given by Equations (10) through (23) are calculated by using only the values of the edge radii R, fillet radii r_i and of the angles α_i and α_{i-2}, all of which are given in engineering drawings.

Now, the important geometrical variables for the volume component under consideration can be calculated:

The segment of perimeter, arc $P_iP_{i-1} = \beta r_i \ . \tag{24}$

The surface area, $S_i = \dfrac{(R_i + R_{i-1})\, H}{2} - A \ . \tag{25}$

The volume, $V_i = \pi(R_i^2 + R_{i-1}^2 + R_iR_{i-1})H/3 - 2\pi R_s A \tag{26}$

The radius of the center of gravity, obtained from $R_{Gi} = (R_{GC}S_C - A R_s)/S_i \ . \tag{27}$

In Equation (27), the radius R_{GC} is the radius of the center of gravity of the half-truncated cone described by P_i and P_{i-1}. R_{GC} is calculated by applying Equation (9). S_C is the surface area of the same half cross section of the truncated cone and is calculated with Equation (6). All other quantities used in Equations (24) through (27) are calculated by using one or more of Equations (10) through (23).

Truncated Cone With Corner

The half cross section of a volume component with a corner is shown in Figure 4a for positive draft angles and in Figure 4b for negative draft angles. Again, the edge radius, R, the corner radius, r_i, and the angles α_i and α_{i-2} are given in the engineering drawing of the forging.

Equations (10) through (21) are still valid for calculating various geometrical quantities shown in Figure 4a.

The angle γ is given by

$$\gamma = \frac{\pi}{2} - \beta/2 - \left| \alpha_{i-2} \right| \quad \text{for } \alpha_{i-2} > 0 \text{ (Figure 3a)} \tag{28a}$$
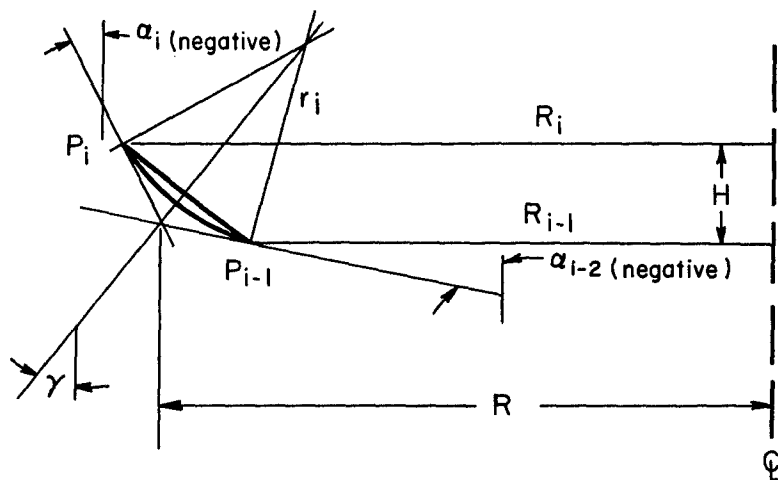
$$\gamma = \frac{\pi}{2} - \left| \alpha_{i-2} \right| + \beta/2 \quad \text{for } \alpha_{i-2} < 0 \text{ (Figure 3b)} \ . \tag{28b}$$

The radius for the center of gravity of the circular segment is given by

$$R_s = R - \Delta x \ . \tag{29}$$
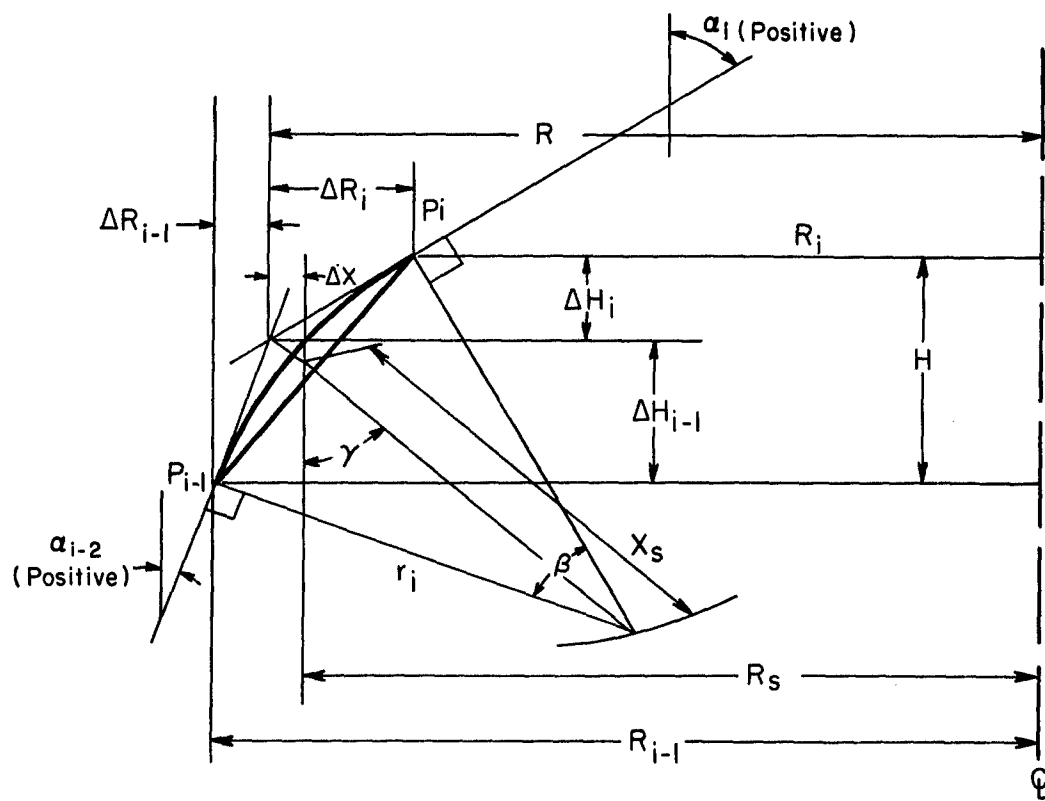
a. Positive Draft Angles

b. Negative Draft Angles

FIGURE 4. SYMBOLS USED IN DESCRIBING THE GEOMETRY OF A
TRUNCATED CONE WITH CONVEX FILLET

The following quantities can now be calculated:

$$\text{The segment of perimeter, arc } P_i P_{i-1} = \beta \, r_i \quad . \tag{30}$$

$$\text{The surface area, } S_i = \frac{(R_i + R_{i-1}) \, H}{2} + A \quad . \tag{31}$$

$$\text{The volume } V_i = \pi(R_i^2 + R_{i-1}^2 + R_i R_{i-1})H/3 + 2\pi \, R_s A \quad . \tag{32}$$

The radius of the center gravity for the entire volume component is

$$R_{Gi} = (R_{GC} \, S_C + A \, R_s)/Si \quad , \tag{33}$$

where R_{GC}, S_C, R_S, S_i and A are obtained from Equations (9), (6), (29), (31), and (19), respectively.

Thus, Equations (30), (31), (32), and (33) give the necessary geometrical quantities for the half cross section of a truncated cone with a corner radius, as seen in Figure 4a and b.

CALCULATION OF GEOMETRICAL QUANTITIES FOR THE ENTIRE FORGING

The half cross section of an axisymmetric forging is illustrated in Figure 5. The draft angles, α_i, the fillet radii, r_i, the heights between corners, H_{Ci}, and some of the corner radii, $R_{i, i-1}$, are obtained directly from the engineering drawing. For instance, for the example given in Figure 5, the corner radii $R_{2, 3}$, $R_{6, 7}$, and $R_{8, 9}$ are obtained from the drawing. Using the geometrical relationships, the corner radii $R_{4, 5}$ and $R_{10, 11}$ are easily calculated by the computer.

The geometrical quantities necessary for calculating the shape-difficulty factor, the flash dimensions, the forging weight, and the flash weight are calculated by adding or subtracting the quantities determined for each volume component. In Figure 5, for instance, the calculated quantities for volume components within the zone defined by the radii $R_{8, 9}$ and $R_{10, 11}$ must be subtracted from the total. In order to use the "subscripted variables" of the FORTRAN computer language, the dimensions and the angles are subscripted as shown in Figure 5.

Perimeter of the Axial Cross-Sectional Surface

The total perimeter of the axial cross-sectional surface, seen in Figure 5, is obtained by adding all the segments of the perimeters calculated for various cross-sectional components. Thus, considering the axial symmetry of the forgings, the total perimeter P is

$$P = 2 \sum_{i=1}^{n} \overline{P_i P_{i-1}} \quad , \tag{34}$$
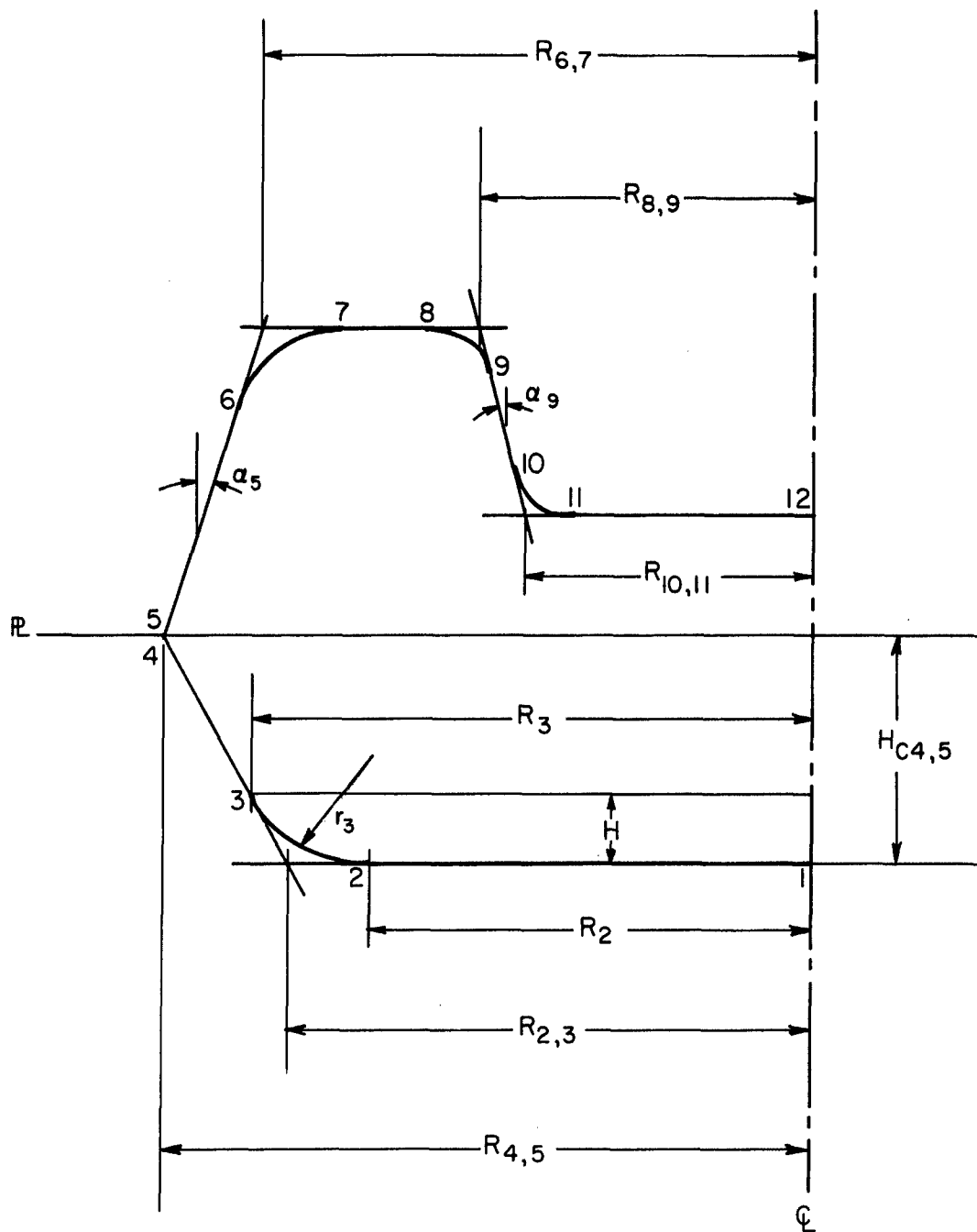
FIGURE 5. DESCRIPTION OF THE FORGING GEOMETRY BY DEFINING
THE CONTOUR OF THE HALF CROSS SECTION WITH VARIOUS
RADII, R_i, FILLET RADII, r_i, AND DRAFT ANGLES, α_i

where

$$\overline{P_i P_{i-1}} = \text{segment of the perimeter obtained from Equations (1), (5), (24),}$$
$$\text{or (30) corresponding to the specific volume component}$$

$$n = \text{number of volume components in the forging.}$$

Equation (34) gives the total perimeter of the axial cross-sectional surface for an axisymmetric forging.

Surface Area of the Axial Cross-Sectional Surface

The total surface area is given by

$$S = 2 \sum_{i=1}^{n} k S_i , \tag{35}$$

where

S_i = surface area of a volume component, from Equations (2), (6), (25) or (31)

n = number of volume components in the forging

k = + 1 or - 1.

The factor k has the value +1 if the surface area of that volume component must be added to the total. If that surface area must be subtracted from the total, as, for instance, for the volume components within the zone defined by $R_{8,9}$ and $R_{10,11}$ of Figure 5, then $k = -1$.

Equation (35) gives the total surface area of the axial cross-sectional surface for an axisymmetric forging.

Volume of the Forging

The total volume of the forging is calculated by

$$V = \sum_{i=1}^{n} k V_i , \tag{36}$$

where

V_i = volume of a volume component, from Equations (3), (7), (26), or (32).

For n and k, the same considerations are valid as in Equation (35), which was used for calculating the area of the cross-sectional surface.

Equation (36) gives the total volume of an axisymmetric forging calculated from the volume components.

Radius of Center of Gravity of the Half Cross Section

The radial distance from the axis to the center of gravity of half of the cross section is calculated by

$$R_G = \left(\sum_{i=1}^{n} k \, R_{Gi} S_i \right) \Big/ S \ , \tag{37}$$

where

R_{Gi} = radius of the center of gravity for a volume component, from Equations (4), (9), (27), or (37)

S_i = surface area of a volume component, from Equations (2), (6), (25), or (31)

n = number of volume components in the forging

k = +1 if the volume of that component is added to the total

= -1 if the volume of that component is subtracted from the total.

After the radii of centers of gravity are determined for the half cross sections of all volume components, the radius of center of gravity for the half cross section of the entire forging is obtained with Equation (37).

COMPUTER PROGRAM TO CALCULATE DESIGN VARIABLES FOR AXISYMMETRIC FORGINGS

The geometrical relationships derived in this report are computerized in order to calculate the necessary variables for obtaining the volume, the flash thickness, and the flash width of the forging. The computer program is given in Appendix D. The FORTRAN symbols used to designate various geometrical variables are listed in Appendix C. The practical use of this computer program is described below by using the half cross section of the example forging obtained from literature and shown in Figure 6.[2]

In order to use this computer program, the user is not required to know the details of the mathematics or of the programming involved. He must, however, know how to prepare the input data for the program. However, the details of the geometrical derivations and of the computer program are given in this report so that those interested in research and development can use this information for future expansion of the present approach.

Program Input

The input data for the computer program are obtained from the engineering drawing of the forging, in which all the draft angles and the fillet radii, but not necessarily all the corner radii (or diameters), are given. The unspecified dimensions are calculated by the computer from the input data. The input data, punched on IBM cards, are given in Table 1 for the forging shown in Figure 6.

Following Table 1, the first line (or the first IBM card) contains (a) the number of corners or fillets below the parting line starting with the point at center line and (b) the number of corners above the parting line starting with the corner at parting line as seen in Figure 6.

TABLE 1. INPUT DATA FOR THE EXAMPLE FORGING OF FIGURE 6 (EACH LINE CORRESPONDS TO ONE IBM CARD)

	Computer Card Column Number					
10	20	30	60	50	60	
7	9					Corner or Fillet
k	R_i	H_{ci}	r_i	α_i	f	No. in Figure 6
1	0.0000	0.0000	0.0000	-90.0000	0.0000	1
1	0.7870	0.0000	0.2360	-6.0000	0.0000	2
1	0.0000	0.3940	0.1180	-90.0000	1.0000	3
1	1.3790	0.0000	0.3940	-6.0000	0.0000	4
1	0.0000	0.5900	0.1180	-90.0000	1.0000	5
1	0.0000	0.0000	0.3940	-6.0000	-1.0000	6
1	2.7570	0.3940	0.0000	0.0000	0.0000	7
1	2.7570	0.0000	0.0000	6.0000	0.0000	1
1	0.0000	0.1970	0.1575	90.0000	1.0000	2
1	2.1650	0.0000	0.1970	5.7000	0.0000	3
1	0.0000	1.5750	0.1970	90.0000	1.0000	4
-1	0.0000	0.0000	0.1970	9.0000	-1.0000	5
-1	1.1820	0.9850	0.1575	90.0000	0.0000	6
-1	0.0000	0.0000	0.1970	9.0000	-1.0000	7
-1	0.5910	0.7870	0.1970	90.0000	0.0000	8
-1	0.0000	0.0000	0.0000	90.0000	0.0000	9
0.2830	5.5140	5.5140	0.3935	0.1967	3.1450	
ρ	D_o	D_c	h_o	h_A	H_s	

Each line in the main body of Table 1 represents the data for a corner point. All dimensions are given in inches. As seen in Table 1, the following quantities are punched on one card and given in one line:

k = +1 if the volume component is to be added to the total volume; otherwise, k = -1. The role of k is already discussed in Equations (35), (36), and (37).

R_i = corner radius; R_i = 0 if that corner radius is not available in the engineering drawing, as seen for the third corner, Table 1 and Figure 6.

H_{ci} = axial distance between two consecutive corners.

r_i = fillet radius.

α_i = angle between the i'th and (i + 1)th corner, as discussed in deriving the geometrical relations for basic volume components.

f = 0, if the corner radius R_i is obtained from the engineering drawing.

f = + 1, if the corner radius must be calculated from the radius of (i-1)th corner, as for the third corner in Figure 6.

f = - 1, if the corner radius R_i must be calculated using the (i+1)th corner, as for the sixth corner in Figure 6.

The last card of the input data contains the following information:

ρ = density of the workpiece material in lb/in.^{3}

D_o = diameter of the initial round stock

D_c = maximum diameter of the forging, i.e., diameter of the circumscribing cylinder

h_o = minimum distance between flat surfaces upon which stock was resting when dies were closed

h_A = distance between internal and external parting lines

H_s = final height of the forging.

The input data given in Table 1 are obtained from the drawing of the example forging shown in Figure 6 by following the conventions described above.

Program Calculations and Output

Using the input data, the program first calculates all the edge radii for the half cross section. It then divides the forging into volume components and determines for the cross section of every volume component (1) the segment of the perimeter, (2) the area of the half cross section, (3) the volume, and (4) the center of gravity.

With these values already calculated, the perimeter, the surface area of the half cross section, the center of gravity of the half cross section, and the volume are calculated for the entire forging. These calculations are carried out by using the formulas developed earlier in this report, and the results are printed out.

At this point, all the variables necessary for calculating the shape-difficulty factor are known. Using the formulas given in the second interim topical report[1] and in Appendix A, the value of the shape-difficulty factor is calculated and printed out.
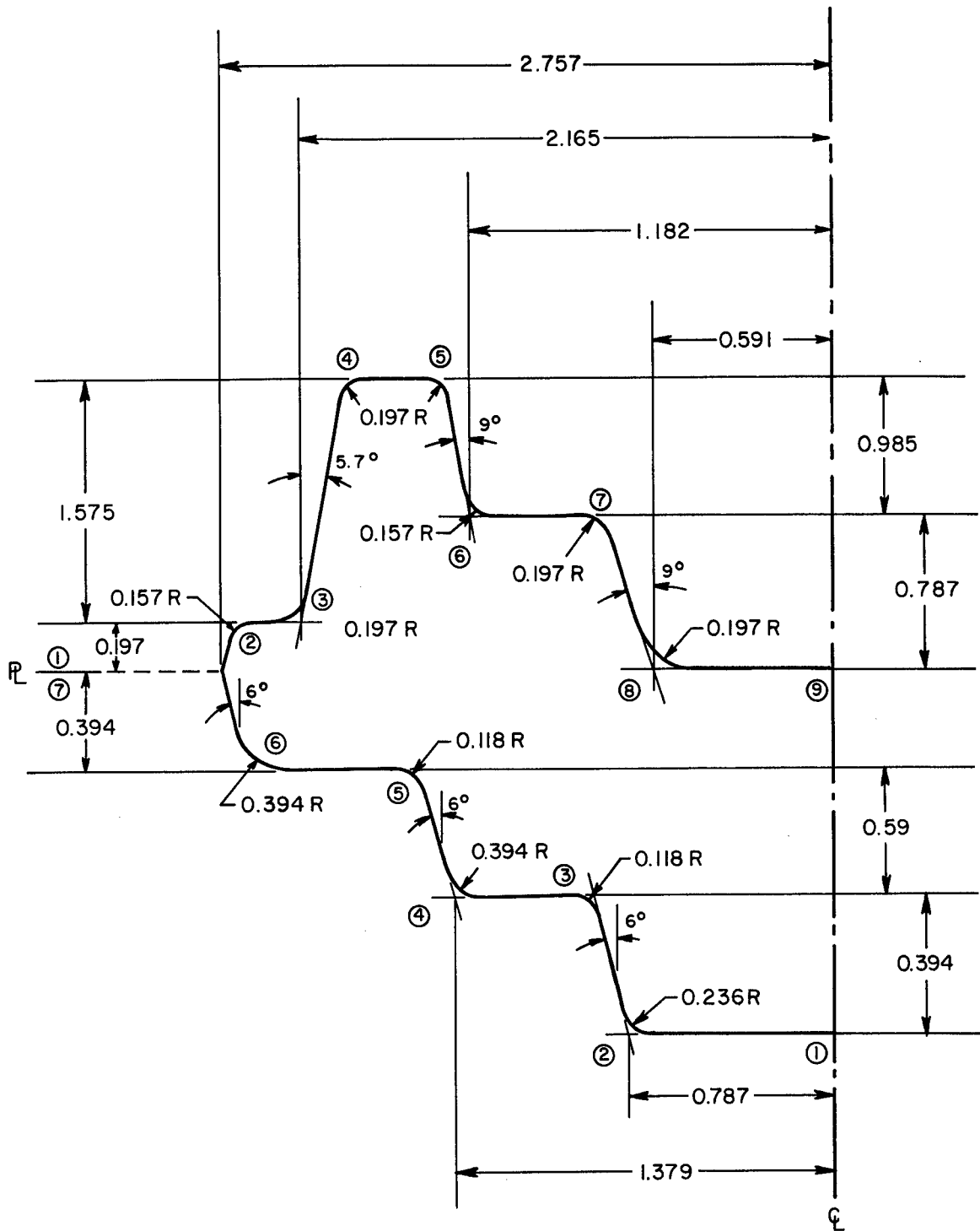
17

FIGURE 6. AXIAL HALF CROSS SECTION OF AN AXISYMMETRIC
FORGING ILLUSTRATING THE INPUT DATA TO COM-
PUTER PROGRAM[2]

All dimensions are given in inches.

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The flash thickness is calculated by using the empirical formula suggested by Wolf.[1] For the computation of the flash ratio, the formula suggested by Wolf is used if the forging weighs less than 1 pound. Otherwise, Teterin and Tornovskij's formula is applied for both in calculating the flash ratio and the flash weight. All these formulas were discussed in detail in the second interim topical report and are given in Appendix B.

The output of the computer program for the example forging shown in Figure 6 is given below:

PERIMETER, SURFACE, VOLUME, R OF C. GRAVITY.
PERIMETER = 18.08550 SURFACE = 8.47459.
VOLUME = 33.25583 RADIUS OF C. OF GRAVITY = 1.24910.
SHAPE DIFFICULTY FACTOR IS 2.02221.
FORGING WEIGHT WITHOUT FLASH IS 9.41140.
FLASH THICKNESS, FLASH WIDTH, FLASH RATIO ARE 0.11403 0.46062 4.03952.
FORGING WEIGHT, FLASH WEIGHT, TOTAL WEIGHT 9.41140 1.04123 10.45263.
THE PROJECTED AREA INCLUDING FLASH IS 32.52509.

The calculated quantities useful for the design of the forging shape are

(1) Shape-difficulty factor
(2) Forging weight with and without flash
(3) Flash thickness
(4) Flash width
(5) The projected area, including flash.

Thus, this computer program calculates in very short time some of the useful variables for the overall design of the forging process.

APPLICATION TO PRACTICAL FORGINGS

The computer program developed in the present study is applied to various axisymmetric steel forgings. Dimensions for most forgings were obtained from the literature and some were supplied by the Steel Improvement and Forge Company.

Guha[2] in his dissertation analyzed the forging shown in Figure 6. He studied the effect of draft angles and fillet radii upon die fill, forging load, and forging energy in forging 1043 and 1045 steels. He carried out experiments under a mechanical press and a counterblow hammer. The actual design values used by Guha for the forging seen in Figure 6 are compared below with the calculated values:

	Actual	Calculated With the Computer Program
Shape-difficulty factor	Not calculated	2.022
Forging volume	Not calculated	33.26 in.^{3}
Forging weight (without flash)	Not calculated	9.41 lb
Forging weight (with flash)	12.29 lb (calculated from stock dimensions)	10.5 lb

	Actual	Calculated With the Computer Program
Flash thickness in die	0.12 in.	0.114 in.
Flash width in die	0.59 in.	0.46 in.
Flash ratio in die	5	4.04

The above comparison clearly shows that the flash dimensions determined by the computer program are close to the actual values used in Guha's experiments. The flash and scale losses used by Guha are about 30 percent of the actual forging weight, while the flash losses predicted by the computer program are 12.0 percent of the forging weight.

The forging analyzed in the present study on "Mechanics of Closed-Die Forging" is illustrated in Figure 7.[1] This forging was designed before the present computer program was developed. Selection of the flash dimensions of the forging are based solely on experience, while the values for the total volume and weight were obtained by using the same empirical formulas used in the computer program. Forging experiments on this shape with lead at room temperature, with 6061 aluminum at 800 F, and with 1020 steel at 2100 F are now completed. During these trials, the forging shown in Figure 7 was completely filled for all three materials. The actual and the calculated design values for this forging are given below:

	Actual	Calculated With the Computer Program
Shape-difficulty factor	--	1.316
Total forging weight	3.42 lb	3.42 lb
Flash thickness in die	0.1 in.	0.085 in.
Flash width in die	0.5 in.	0.41 in.
Flash ratio in die	5	4.8

The above comparison shows that the theoretical values are within the useful range of the empirically estimated values used in experiments.

Brill, in his study on modeling of the hot forging process, used the forging shape seen in Figure 8.[3] He forged model materials such as wax, lead, plasticine and plastics, and 1043 steel in the same die. The actual and the calculated significant parameters are given below:

	Actual	Calculated With the Computer Program
Shape-difficulty factor	--	1.134
Forging weight without flash	0.336 lb	0.336 lb
Forging weight with flash	0.36 lb (calculated from stock dimensions)	0.41 lb
Flash thickness in die	0.079 in.	0.058 in.
Flash width in die	0.394 in.	0.236 in.
Flash ratio in die	5	4.06

The comparison indicates that the flash dimensions predicted by the computer program are close to the actual values. The flash weight predicted by the computer program is 22 percent of the forging weight, while the actual flash weight is only 7.2 percent of the forging weight. A careful examination of the photographs of forgings given in Brill's
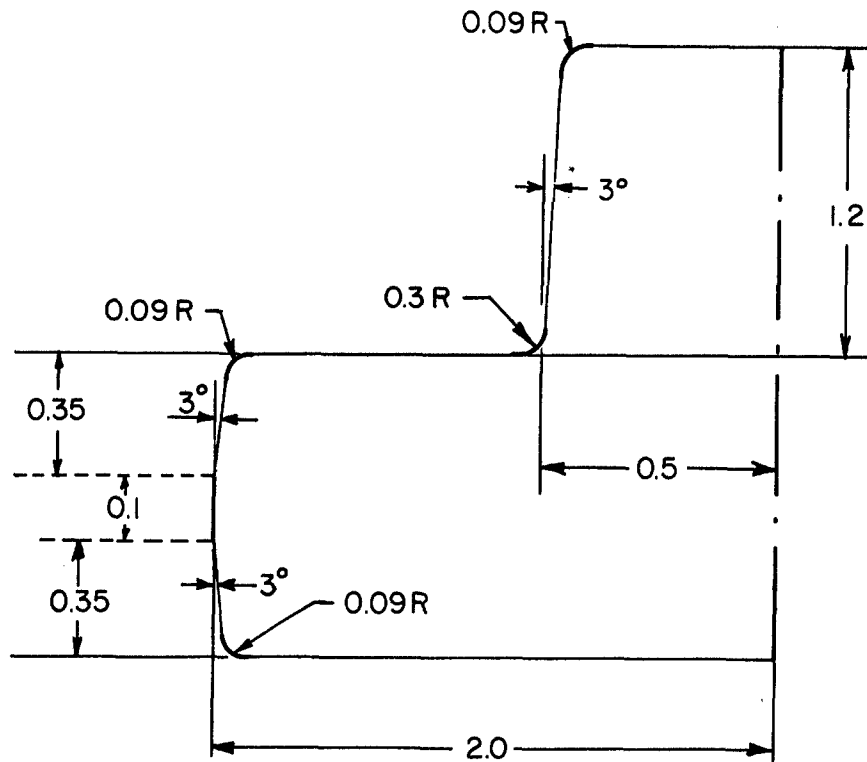
FIGURE 7.   AXISYMMETRIC FORGING USED IN THE PRESENT
PROGRAM FOR CLOSED-DIE FORGING STUDIES
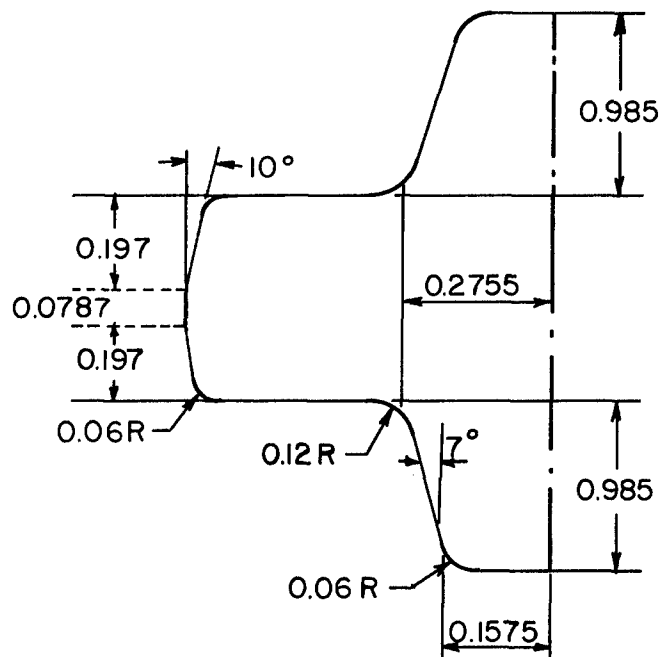
All dimensions are given in inches.

FIGURE 8.   AXISYMMETRIC FORGING USED IN BRILL'S
EXPERIMENTS[3]

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dissertation indicates, however, that the die cavity was not always completely filled. The top of the spikes on the top and bottom of some forgings do not appear to have the exact contour of the die cavity at the spike.[3] Consequently, the theoretically predicted values for flash weight and flash dimensions seem to be more realistic design values than the ones used by Brill.[3]

Tolkien made an extensive experimental study on various lubricants in closed-die forging.[4] He evaluated the friction and the sticking forces of lubricants by using the closed-die forging seen in Figure 9. The actual and the calculated design parameters for this forging are given below:

	Actual	Calculated With the Computer Program
Shape-difficulty factor	--	1.014
Forging weight without flash	0.260 lb	0.260 lb
Forging weight with flash	0.336 lb	0.317 lb
Flash thickness in die	0.0552 in.	0.0564 in.
Flash width in die	0.138 in.	0.23 in.
Flash ratio in die	2.5	4.1

The agreement between theoretical and actual values is good. The flash thicknesses are nearly identical, while the theoretical flash width is slightly larger. The flash weight predicted by computer calculations is less than the actual weight used by Tolkien (22 percent versus 29.2 percent).

One of the participating companies in this program, Steel Improvement and Forge Company, supplied the die and forging drawings for the axisymmetric forging seen in Figure 10. Using the dimensions given in Figure 10, the computer program was used to calculate the following parameters:

Shape-difficulty factor	1.8
Forging weight without flash	5.74 lb
Forging weight with flash	6.33 lb
Flash thickness	0.100 in.
Flash width	0.431 in.
Flash ratio	4.35

These values appear to be reasonable for forging the shape seen in Figure 10 from low-alloy steel. In SIFCO's actual forging, the material was 347 stainless steel, with one blocker die and one finishing die used. It is interesting to observe that SIFCO's forging (Figure 10) has a shape-difficulty factor of 1.8, while Guha's forging (Figure 6) has a shape-difficulty factor of 2.02. Guha could forge his shape without using a blocker die because the workpiece material was low-alloy steel. SIFCO's example illustrates the well-known fact that, in addition to the geometrical shape-difficulty factor, factors describing the influence of forging material, die wear, and forging tolerances must also be considered in designing a forging process. Those latter parameters are not included in the computer program described in this report.
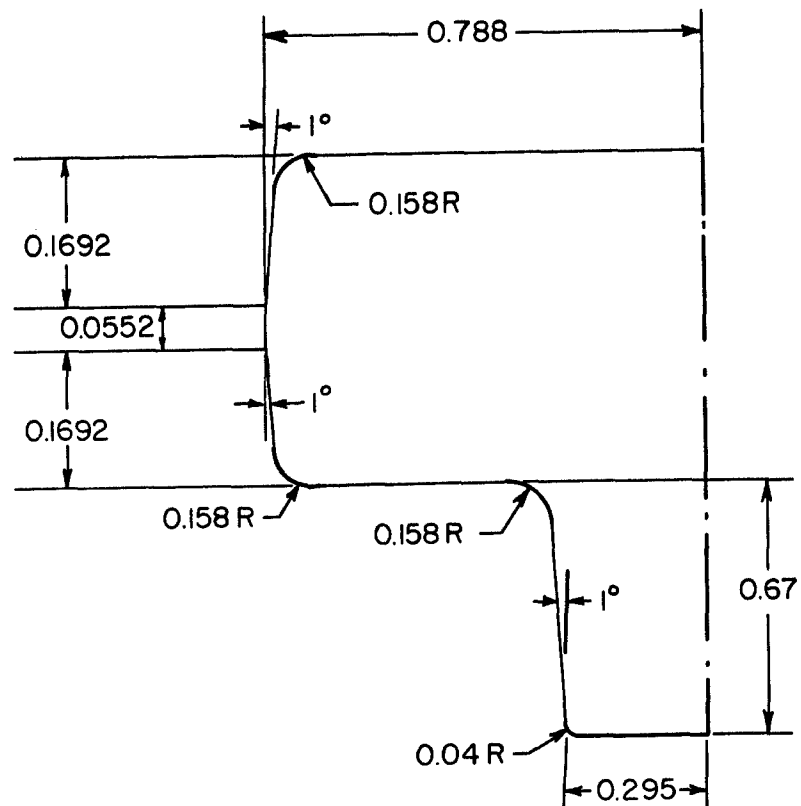
FIGURE 9. AXISYMMETRIC FORGING USED BY TOLKIEN IN STUDYING LUBRICATION EFFECTS IN CLOSED-DIE FORGING[4]
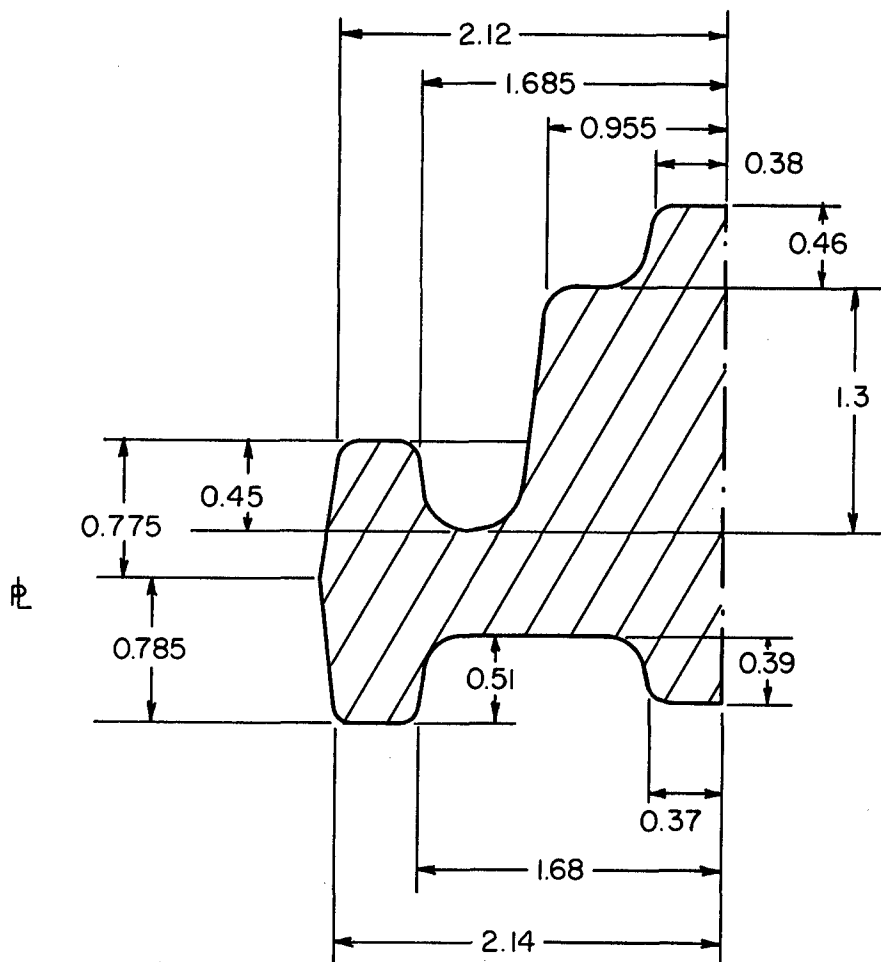
All dimensions are given in inches.

FIGURE 10. AXISYMMETRIC FORGING DIMENSIONS SUPPLIED BY
SIFCO FOR THE PRESENT PROGRAM

All draft angles = 7°; all fillet radii = 0.25 in.; all corner
radii = 0.12; other dimensions shown in inches.

DISCUSSION

The determination of the number of preforming operations, the design of flash, and the prediction of flash and scale losses are significant steps in designing a forging process. The flash geometry has a marked influence upon die loads and stresses and upon die filling. The prediction of flash weight, including scale losses, is a very important factor in the overall cost of large-quantity-production forgings. The blocker shapes are necessary in forging complex shapes of difficult-to-forge materials, and they add to forging costs. It normally takes extensive experience to reasonably estimate these variables and to design the forging process, and they are not included in the current computer program. It may be possible to handle such decisions later as experience and data accumulate and are introduced into the program.

The difficulty in forging a part depends upon various factors, such as the geometrical shape of the forging, the forging material, the forging tolerances, and the expected die wear. The "shape-difficulty factor" has been suggested for axisymmetric shapes by Soviet workers. [1] Using the shape-difficulty factor described in Appendix A and statistically obtained empirical equations given in Appendix B, it appears to be possible to predict the flash dimensions and the flash weight for axisymmetric low-alloy steel forgings. This procedure is extended to calculate the volume of a forging, also, and it is programmed for a computer in FORTRAN language. The program uses only information given in the engineering drawing and calculates the total weight of the forging (forging weight and flash weight). In order to use this computer program, the user is not required to know the details of the mathematics or the programming involved. He must only know how to prepare the input data, as shown in Table 1.

The computer program is applied to various forgings, and results have been compared with actual experimental data. The agreement between theoretical-empirical predictions and with design data developed experimentally (or suggested by extensive forging experience) is very good. The developed computer program is now available to interested forging companies. It could be used for a systematic analysis of existing forging data, for making cost estimates after incorporating in-house cost factors, or for designing axisymmetric forgings with a minimum amount of additional effort.

The information presented in this report is not intended to be a ready answer for design problems of individual forgers. In order to establish a more exact analysis of the forging process, the concept of shape-difficulty factor must be complemented by experimental-empirical factors describing the effect of forging material, forging tolerances, and die wear. Every company could find and develop this information to suit its own needs and operations. The concept of a shape-difficulty factor could be further extended to nonaxisymmetric forgings, if there is interest within the industry for this kind of developmental work.

REFERENCES

(1) Altan, T., Henning, H. J., and Sabroff, A. M., "Methods for Estimating Flash-Gap Dimensions and Flash Weight in Closed-Die Steel Forging", Second Interim Topical Report to AMMRC, Watertown, Massachusetts, January 30, 1969.

(2) Guha, S. P., "Einfluss der Abrundungen an den Werkzeugen beim Gesenkschmieden
     auf Kraft-und Arbeitsbedarf sowie den Steigvorgang" (Influence of Fillet Radii on
     Load and Energy Requirements and on Die Fill in Closed-Die Forgings). Disserta-
     tion, Aachen, 1964.

(3) Brill, K., "Modellwerkstoffe für die Massivumformung von Metallen" (Model Mate-
     rials for Forging of Metals), Dissertation, Hannover, 1963.

(4) Tolkien, H., "Schmierwirkungen in Schmiedegesenken" (Lubrication Effects in Forg-
     ing Dies), Dissertation, Hannover, 1961.

APPENDIX A

THE SHAPE-DIFFICULTY FACTOR FOR
AXISYMMETRIC FORGINGS

APPENDIX A

THE SHAPE-DIFFICULTY FACTOR FOR
AXISYMMETRIC FORGINGS

The shape-difficulty factor for axisymmetric forgings was originally suggested by Teterin, et al.,[1] and was discussed in the second interim topical report. The derivations are summarized in this Appendix.

A shape factor, x_f, is defined as:

$$x_f = \frac{P^2}{F} ,$$
(A-1)

where

P = perimeter of the axial cross-sectional surface

F = surface area of the axial cross-sectional surface.

Since the shape factor x_f is dimensionless, any unit of length can be used for its calculation. A cross section through a 10-in.-diam x 10-in.-high cylinder, for example, has a perimeter of 40 inches and a cross-sectional surface area of 100 inches^2. The shape factor, x_f, would thus be

$$x_f = \frac{40^2}{100} = 16 \text{ (dimensionless)} .$$

To arrive at a factor for expressing complexity of shape, Teterin, et al, considered the cylinder that circumscribes the shape of the forging. Thus, the height, H_c, of the cylinder is equal to the maximum height of the forged shape, and the diameter, D_c, is equal to the largest diameter of the forged shape. The cylinder is considered to represent the simplest shape and any modification of the cylinder to introduce more complexity. Mathematically, the shape factor of any cylinder, x_c, can be expressed as

$$x_c = \frac{P_c^2}{F_c} = \frac{4(H_c + D_c)^2}{H_c D_c} .$$
(A-2)

The authors proposed that a "longitudinal shape" factor, α, be designated to compare any shape with its circumscribing cylinder as follows:

$$\alpha = \frac{x_f}{x_c} .$$
(A-3)

The shape factors x_f and x_c in Equation (A-3) are calculated from Equations (A-1) and (A-2), respectively. If $x_f = x_c$, the value for α_c would be 1, expressing the longitudinal shape factor for a simple cylinder.

Teterin, et al, recognized that projections on circular forgings (e.g., shaft or rims) become progressively more difficult to forge as the projections are located at progressively greater distances from the axis of the forging. To accommodate such variations in forging difficulty, the authors proposed a "lateral" shape factor, β, which is used to express the degree of forging intricacy in the lateral direction. Thus,

$$\beta = \frac{2 R_g}{R_c} \quad , \tag{A-4}$$

where

R_g = radial distance from the axis to the center of gravity of half of the cross section

R_c = maximum radius of the forged piece which equals the radius of the circumscribing cylinder.

For a cylinder, Equation (A-4) gives $\beta_c = 1$.

In summary, the parameters α and β define the relative difficulty of forging a given workpiece in two different planes. A shape-difficulty factor, S_f, incorporating both of these parameters, α and β, is defined as

$$S_f = \alpha \cdot \beta \quad . \tag{A-5}$$

Substituting Equations (A-3) and (A-4),

$$S_f = \frac{x_f}{x_c} \cdot \frac{2 R_g}{R_c} \quad . \tag{A-6}$$

Continuing the substitution for these components, using Equations (A-1) and (A-2),

$$S_f = \frac{\dfrac{P^2}{F}}{\dfrac{P_c^2}{F_c}} \cdot \frac{2 R_g}{R_c} \quad . \tag{A-7}$$

The authors use the subscript 1 to indicate the shape of a forging under study (same as the shape of the forging-die cavity). Thus,

$$S_1 = \frac{\left(\dfrac{P^2}{F} \right)_1}{\left(\dfrac{P_c^2}{F_c} \right)_1} \cdot \frac{2 R_{g1}}{R_{c1}} \quad . \tag{A-8}$$

If the part is being forged in more than one step, a shape-difficulty factor must also be defined for the starting shape of the workpiece, i.e.,

$$S_o = \alpha_o \beta_o = \frac{\left(\dfrac{P^2}{F}\right)_o}{\left(\dfrac{P_c^2}{F_c}\right)_o} \cdot \frac{2R_{g_o}}{R_{c_o}} \quad , \tag{A-9}$$

where the subscript o indicates the shape factor for the workpiece before the forging step under consideration.

If the starting shape is a cylinder, the overall shape-difficulty factor, S, is expressed as

$$S = \frac{S_1}{S_c} \quad . \tag{A-10}$$

Since the shape-difficulty factor for a cylinder $S_c = \alpha_c \cdot \beta_c = 1 \cdot 1 = 1$,

then $$S = S_1 \quad . \tag{A-11}$$

However, if S_o represents the shape-difficulty factor of a preform and S_1 represents that for the final forging shape, the shape-difficulty factor is expressed as

$$S = \frac{S_1}{S_o} \quad . \tag{A-12}$$

In this case, the values for both S_1 and S_o must be calculated using Equations (A-8) and (A-9).

Teterin, et al, conducted a statistical-regression analysis of shape factors determined with these procedures on several shapes of various difficulty. They found that the shape-difficulty factor, S, forging weight, Q, and forging diameter, D_o, represent the most important factors in determining the flash ratio (w/t) for the forgings studied.

In this regard, the determination of shape-difficulty factor S permits the selection of flash dimensions with greater confidence.

APPENDIX B

EMPIRICAL FORMULAS FOR PREDICTING FLASH
DIMENSIONS AND FLASH WEIGHT

APPENDIX B

EMPIRICAL FORMULAS FOR PREDICTING
FLASH DIMENSIONS AND FLASH WEIGHT

Flash Dimensions

Empirical formulas for predicting flash dimensions and flash weight were given in the second topical interim report and are summarized in this Appendix.

The flash thickness is obtained with the equation suggested by Wolf[1] and is given below:

$$t = \frac{(1.13 + 0.89\sqrt{Q/2.2} - 0.017\, Q/2.2)}{25.4} \quad , \tag{B-1}$$

where t is in inches and Q is the forging weight in pounds.

The flash ratio (width/thickness) for forgings weighing more than 1 pound is given by Teterin and Tornovskij's [1] equation:

$$\frac{w}{t} = -0.02 + 0.0038\, S\left(\frac{D_o}{t}\right) + \frac{4.93}{(Q/2.2)^{0.2}} \quad . \tag{B-2}$$

For forgings weighing less than 1 pound, the equation established by Wolf[1] is suggested:

$$\frac{W}{t} = 1.25 \exp(-1.09\, Q/2.2) + 3 \quad . \tag{B-3}$$

In both formulas,

W = flash-land width, in.

D_o = diameter of the initial round stock, in.

S = dimensionless shape-difficulty factor (S designates the difficulty involved in forging a shape, increasing with increasing shape complexity).

Q = forging weight, lb.

Flash Weight

The following variables usually are considered in estimatimating the amount of flash in filling a forging-die cavity:

(1) Weight of the forging

(2) Dimensions of the flash gap

(3) The location of the internal and external parting lines

(4) Shape difficulty.

The experienced die engineer usually considers a base-line flash-metal loss of about 5 percent of the forging weight and adjusts this value according to respective geometries of the flash and any internal punch-outs. Extra allowances for shape complexity are generally arbitrary, and, depending on the individual's experienced judgment, the allowances may be as much as an additional 5 percent of the forging weight. For example, a 100-lb axisymmetric forging having a 5-lb punch-out and a complex configuration might be estimated to require

5 lb for flash

5 lb for a punch-out

5 lb extra for shape complexity

15 lb total allowance for flash losses.

Such estimates usually are checked out by forging a few billets representing a range of weights that bracket the calculated weight. The results of these "tryout" runs then are used as a basis for finalizing the cutting weight for the billets.

Teterin and Tornovskij[1] conducted a statistical analysis of data on numerous axisymmetric forgings aimed at developing mathematical procedures for estimating flash-metal losses. The investigators derived a dimensionless parameter, γ, which takes into account the original stock dimensions, the dimensions of the final forging, and the vertical distance between internal and external parting lines (Figure B-1). The formula for γ is

$$\gamma = \frac{H_s}{h_o + h_A} \quad , \tag{B-4}$$

where

H_s = final height of the forging

h_o = minimum distance between flat surfaces upon which stock was resting when dies were closed

h_A = distance between internal and external parting lines.
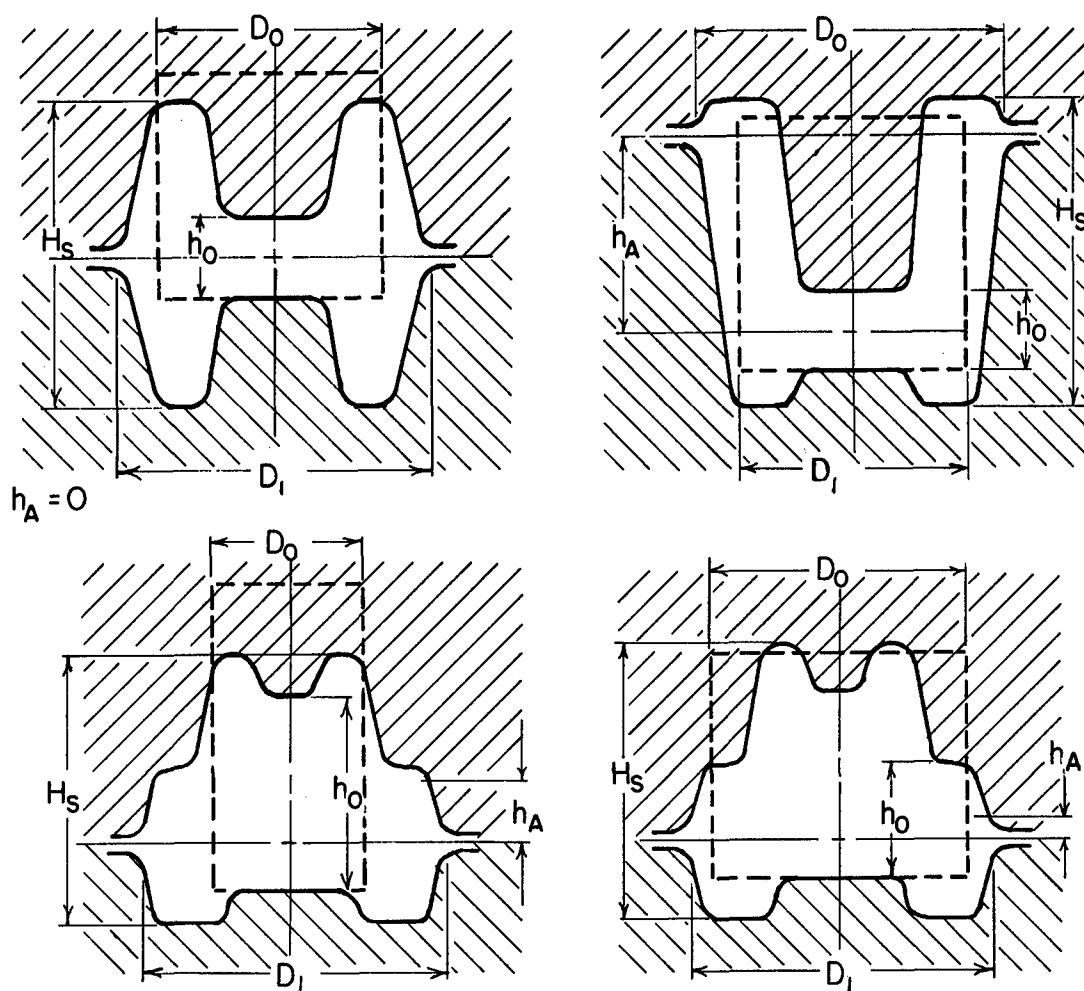
FIGURE B-1. VARIABLES INDICATING THE SHIFT OF THE EXTERNAL
PARTING LINE AND THE INITIAL POSITION OF THE
STOCK IN THE DIES [1]

Statistically analyzing data from a sufficiently large number of forgings, the authors obtained the following expression for calculating the weight of flash:

$$Q_f = \frac{(K_1 - K_2)}{100} \cdot Q \quad , \tag{B-5}$$

where

Q_f = weight of the flash

Q = weight of the forging

and the parameters K_1 and K_2 are determined from

$$K_1 = 0.54 + 15.44 \, (Q/2.2)^{-0.2} \, (1 + 0.00757\eta), \quad Q \text{ in lb}, \tag{B-6}$$

and

$$K_2 = 0.7026 \, (1 + 0.01969\eta) \, w/t \quad , \tag{B-7}$$

where w/t is obtained from Equations (B-2) or (B-3).

The parameter, η, represents a dimensionless expression for shape that incorporates the shape factor, S, the shape-change parameter, γ, and the diameters of the stock (D_o) and the final forging (D_1) thus:

$$\eta = \left[S \left(\frac{D_o}{D_1} \right)^2 \gamma^2 \right] \quad , \tag{B-8}$$

where

S is the shape-difficulty factor

and

γ is obtained from Equation (B-4).

APPENDIX C

SYMBOLS USED IN THE FORTRAN PROGRAM

APPENDIX C

SYMBOLS USED IN THE FORTRAN PROGRAM

NR1 = number of corners in a half cross section <u>below</u> the parting line, including the corners on the parting line and on the axis.

NR2 = number of corners in a half cross section <u>above</u> the parting line, including the corners on the parting line and on the axis.

MARK(I) = +1 if the volume component must be added to total

-1 if the volume component must be subtracted from total.

R(I) = radius of i'th corner, R in Figures 2 and 3 or $R_{i,i-1}$ in Figure 5.

CH(I) = axial distance between two consecutive corners, Figure 5.

FR(I) = fillet radius at the i'th corner, Figure 5.

ALFA(I) = draft angle between the i'th and (i+1)th corners, Figure 5.

PER(I) = 0, if the radius of the i'th corner is given

+1 if the radius of the i'th corner must be calculated from the radius of (i-1)th corner

-1 if the radius of the i'th corner must be calculated from the radius of (i+1)th corner.

segment of the perimeter $\overline{P_i P_{i-1}}$ from Equations (1), (5), (24) or (30).

DENS = density of the forging material, lb/in.^{3}.

DIAM = initial stock diameter.

DCYL = diameter of the cylinder circumscribing the forging.

HCYL = height of the cylinder circumscribing the forging.

TAHZ = minimum distance between flat surfaces upon which stock was resting when dies are closed.

SURF(I) = surface area of the half cross section of a volume component, from Equations (2), (6), (25), or (31).

VOL(I) = volume of a volume component, from Equations (3), (7), (26), or (32).

RG(I) = radius of center of gravity for a half cross section of a volume component.

TPER   = perimeter of the axial cross section of an axisymmetric forging.

TSURF   = area of the cross-sectional surface.

TVOL   = volume of the forging.

RGT   = radius of center of gravity of the half cross section.

SHAPE   = shape-difficulty factor, as described in the Second Interim Topical Report.[1]

WEIGH   = weight of forging without flash.

FTHICK   = flash thickness.

RATIO   = flash-width-to-thickness ratio.

FWIDTH   = flash width.

WTOT   = total forging weight, including flash losses.

AREA   = total plan area of the forging, including flash.

APPENDIX D

FORTRAN COMPUTER PROGRAM FOR CALCULATING DESIGN
PARAMETERS IN AXISYMMETRIC FORGINGS

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```
      PROGRAM SHAPF(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C##                    DETERMINATION OF SHAPE FACTOR IN FORGING
C##              MODIFICATION  IF BEGINNING AND END CORNERS ARE
C##                 NOT FLAT
      COMMON R(100),NR,CH(100),ALFA(100),PER(100),SURF(100),VOL(100),
     1RG(100),FR(100),MARK(100),DELH(100)
      PI=3.1415926536
C##                                R(I)= RADIUS OF THE FORGING AT VARIOUS
C##                                LOCATIONS
C##                                NR= NUMBER OF CORNERS ON ONE HALF OF THE
C##                                FORGING
C##                                CH(I)= AXIAL DISTANCE BETWEEN I-TH AND
C##                                (I-1)TH CORNER
C##                                ALFA(I)= ANGLE OF THE TAPER AT THE I-TH
C##                                CORNER WITH THE AXIS
C##                      PER(I)= PERIMETER OF A SLICE
C##                      SURF(I)=SURFACE AREA OF A SLICE
C##                      VOL(I)=VOLUME OF A SLICE
C##                                FR(I)= FILLET RADIUS BETWEEN THE I-TH AND
C##                                (I-1)TH CORNERS ,FR(I)=0. FOR SHARP CORNER
C##                            MARK(I)=1 FOR INCREASING VOLUME
C##                          MARK(I)=-1 FOR DECREASING VOLUME
C##              NR1=NUMBER OF CORNERS FROM BEGIN TO PARTING LINE
C##              NR2=NUMBER OF CORNERS FROM PARTING LINE TO END
C##              IN PER(I) WE STORE SIGNS TO CALCULATE SOME R(I)S

      READ 21,NR1,NR2
      PRINT 22,NR1,NR2
      NR=(NR1-1)*2+(NR2-1)*2
      NRD=(NR1-1)*2
      NRDM=NRD-1
      PRINT86
      DO 81 I=1,NRDM,2
      READ 82,MARK(I),R(I),CH(I),FR(I),ALFA(I),PER(I)
      PRINT82,MARK(I),R(I),CH(I),FR(I),ALFA(I),PER(I)
      IF(I.EQ.1)GO TO 81
      PER(I-1)=PER(I)
      MARK(I-1)=MARK(I)
      R(I-1)=R(I)
      CH(I-1)=CH(I)
      FR(I-1)=FR(I)
   81 ALFA(I+1)=ALFA(I)
      READ 82,MARK(NRD),R(NRD),CH(NRD),FR(NRD),ALFA(NRD),PER(NRD)
      PRINT82,MARK(NRD),R(NRD),CH(NRD),FR(NRD),ALFA(NRD),PER(NRD)
      NRDP=NRD+1
      NRM=NR-1
      DO 83 I=NRDP,NRM,2
      READ 82,MARK(I),R(I),CH(I),FR(I),ALFA(I),PER(I)
      PRINT82,MARK(I),R(I),CH(I),FR(I),ALFA(I),PER(I)
      IF(I.EQ.NRDP) GO TO 83
      MARK(I-1)=MARK(I)
      PER(I-1)=PER(I)
      R(I-1)=R(I)
      CH(I-1)=CH(I)
```

```
      FR(I-1)=FR(I)
   83 ALFA(I+1)=ALFA(I)
      READ 82,MARK(NR),R(NR),CH(NR),FR(NR),ALFA(NR)
      PRINT82,MARK(NR),R(NR),CH(NR),FR(NR),ALFA(NR)
      NRMIN=NR-1
      DO84I=1,NRMIN,2
      IF(I.EQ.1)GO TO 84
      IF(R(I).NE.0.)GO TO 84
      ANGLE=ALFA(I-2)
      ANGLE=ANGLE*PI/180.
      IF(PER(I).LT.0.)GO TO 85
      R(I)=R(I-2)-PER(I)*TAN(ANGLE)*CH(I)
      R(I-1)=R(I)
      GO TO 84
   85 ANGLE=ALFA(I)
      ANGLE=ANGLE*PI/180.
      R(I)=R(I+1)-PER(I)*TAN(ANGLE)*CH(I+1)
      R(I-1)=R(I)
   84 CONTINUE
      PRINT22,NR
      PRINT24
      PRINT23,(R(I),I=1,NR)
      PRINT25
      PRINT23,(CH(I),I=1,NR)
      PRINT 29
      PRINT23,(FR(I),I=1,NR)
      PRINT27
      PRINT23,(ALFA(I),I=1,NR)
      PRINT23,(PER(I),I=1,NR)
      PRINT21,(MARK(I),I=1,NR)
      READ 23,DENS,DIAM,DCYL,TAHZ,TAHA,HCYL
      PRINT28,DENS,DIAM,DCYL,TAHZ,TAHA,HCYL
C**                             DENS=DENSITY
C**                             DIAM=STOCK DIAMETER
C**                             DCYL=LARGEST DIAMETER OF FORGING
C**                             TAHZ=MINIMUM DISTANCE BETWEEN FLATS
C**                             TAHA=DISTANCE BETWEEN INTERNAL AND
C**                             EXTERNAL PARTING LINES
C**                             HCYL=TOTAL HEIGHT OF FORGING
      TVOL=0.
      TPER=0.
      TRGS=0.
      TH=0.
      DO32I=1,NR
   32 ALFA(I)=ALFA(I)*PI/180.
      NLIM=NR-1
C**                   START CALCULATIONS
      DO131I=3,NLIM,2
      IF(ALFA(I-1).EQ.0.)GO TO 41
C**                             THIS CHECKS THE PARTING LINE WHICH IS
C**                             CONSIDERED AS CYLINDER
      DIFF=ALFA(I-2)-ALFA(I)
      BETA=ABS(DIFF)
      PER(I)=BETA*FR(I)
      B2=BETA/2.
```

```
      T2=TAN(B2)
      S2=SIN(B2)
      C2=COS(B2)
      FR1=FR(I)*T2
      DELRM=FR1*SIN(ALFA(I-2))
      DELR =FR1*SIN(ALFA(I))
C**                                   CORNER RADIUS WAS ORIGINALLY STORED AT
C**                                   BOTH R(I) AND R(I-1)
      DELH(I)=FR1*COS(ALFA(I))
      DELH(I)=ABS(DELH(I))
      DELH(I-1)=FR1*COS(ALFA(I-2))
      DELH(I-1)=ABS(DELH(I-1))
      TAH=DELH(I)+DELH(I-1)
      SBETA=SIN(BETA)
      TAS=FR(I)**2*(BETA-SBETA)/2.
      TAXS=2.*FR(I)**3*S2**3/(3.*TAS)
      PALF2=ABS(ALFA(I-2))
      GAMMA=B2+0.5*PI-PALF2
C**                                   MODIFY HERE
      IF(ALFA(I-2).LT.0.)GAMMA=0.5*PI-B2-PALF2
      GAMMA=ABS(GAMMA)
      IF(ALFA(I).GT.ALFA(I-2))GO TO 51
      DELX=(FR(I)/C2-TAXS)*SIN(GAMMA)
      RS=R(I)+DELX
   52 CONTINUE
      R(I)=R(I)-DELR
      R(I-1)=R(I-1)+DELRM
      S1=R(I)+R(I-1)
      SURF(I)=S1*TAH/2.-TAS
      RIRMI=R(I)**2+R(I-1)**2+R(I)*R(I-1)
      VOL(I)=PI*(RIRMI*TAH/3.-TAS*2.*RS)
      RGCON=RIRMI/(3.*S1)
      RG(I)=(RGCON*S1*0.5*TAH-TAS*RS)/SURF(I)
   42 CONTINUE
C**                                   NOW CALCULATE FOR THE TRUNCATED CONE
C**                                   AS DEFINED BY POINTS I-1 AND I-2
      TAH1=CH(I)-DELH(I-1)-DELH(I-2)
C**                                   CH(I)=HEIGHT BETWEEN CORNERS STORED AT
C**                                   BOTH CH(I) AND CH(I-1)
   43 CONTINUE
      RI1=R(I-1)+R(I-2)
      SURF(I-1)=RI1 *0.5*TAH1
      RIRM1=R(I-1)**2+R(I-2)**2+R(I-1)*R(I-2)
      VOL(I-1)=PI*TAH1*RIRM1/3.
      DEN=SIN(ALFA(I-2))
      IF(ALFA(I-2).EQ.0.)DEN=1.
      PER(I-1)=ABS((R(I-1)-R(I-2))/DEN)
      RG(I-1)=RIRM1/(3.*RI1)
      TABS=ABS(DEN)-1.
      TABS=ABS(TABS)
      IF(TABS.GT.0.00001)GO TO 31
      SURF(I-1)=0.
      RG(I-1)=0.
      VOL(I-1)=0.
      GO TO 31
```

```
   41 CONTINUE
C**                              CALCULATIONS FOR CYLINDER AT PARTING LINE
C**                      AND FOR THE ADJACENT TRUNCATED CONE
      RG(I)=R(I)/2.
      SURF(I)=R(I)*CH(I)
      VOL(I)=PI*R(I)**2*CH(I)
      PER(I)=CH(I)
      TAH1=CH(I-1)-DELH(I-2)
      DELH(I)=0.
      GO TO 43
   51 CONTINUE
      PALF2=ABS(ALFA(I-2))
      GAMMA=0.5*PI-B2-PALF2
      IF(ALFA(I-2).LT.0.)GAMMA=0.5*PI-PALF2+B2
      GAMMA=ABS(GAMMA)
      DELX=(FR(I)/C2-TAXS)*SIN(GAMMA)
      RS=R(I)-DELX
      TAS=-TAS
      GO TO 52
   31 CONTINUE
      IK=I+1
      DO132K=1,3
      KK=IK-K
  132 PRINT133,KK,PER(KK),SURF(KK),VOL(KK),RG(KK)
      GAM=GAMMA*180./PI
      PRINT133,I,BETA,DELH(I),DELH(I-1),TAH,R(I),R(I-1),TAH1,GAM
      BETB=BETA*180./PI
      PRINT133,I,BETB,B2,T2,S2,C2,FR1,DELR,DELRM
  131 CONTINUE
      SURF(NR)=0.
      VOL(NR)=0.
      RG(NR)=0.
      PER(NR)=ABS((R(NR)-R(NR-1)))
      TPER=0.
      TSURF=0.
      TVOL=0.
      RGS=0.
C******      CALCULATE PERIMETER,VOLUME,SURFACE AND RAD. OF CENT. OF
C*****              GRAVITY
      DO61I=2,NR
      FMARK=1.
      TPER=TPER+PER(I)
      IF(MARK(I).LT.0)FMARK=-1.
      TSURF=TSURF+FMARK*SURF(I)
      TVOL=TVOL+FMARK*VOL(I)
      RGS=RGS+FMARK*RG(I)*SURF(I)
   61 CONTINUE
      RGT=RGS/TSURF
      TSURF=2.*TSURF
      TPER=2.*TPER
      PRINT 911
      PRINT67,TPER,TSURF,TVOL,RGT
C**                              START CALCULATION OF SHAPE FACTOR
      EXF=TPER**2/TSURF
      EXC=4.*(HCYL+DCYL)**2/(HCYL*DCYL)
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      ALFS=EXF/EXC
      RCYL=DCYL/2.
      BETS =2.*RGT/RCYL
      SHAPE=ALFS*BETS
      PRINT 62,SHAPE,ALFS,BETS
      WEIGH=TVOL*DENS
      PRINT 63,WEIGH,TVOL
C**              FOR FLASH THICKNESS WE USE WOLF-S FORMULA
      T1=WEIGH/2.2046
      FTAT=0.89*T1**0.5-0.017*T1
      FTHICK=(1.13+FTAT)/25.4
C**              FOR FLASH RATIO WE USE WOLF-S FORMULA IF WEIGHT IS
C**              SMALLER THAN 1  LBS.OTHERWISE TETERIN S FORMULA
      IF(WEIGH.LT.1.)GO TO 71
      RATIO=-0.02+0.0038*SHAPE*DCYL/FTHICK+4.93/(T1**0.2)
      GO TO 72
   71 PART=-1.09*T1
      RATIO=1.25*EXP(PART)+3.
   72 CONTINUE
      FWIDTH=RATIO*FTHICK
      PRINT 64,FTHICK,FWIDTH,RATIO
      GAM=HCYL/(TAHZ+TAHA)
      ETA=SHAPE*DIAM**2*GAM**2/DCYL**2
      AK2=0.7026*(1.+ETA*0.01969)*RATIO
      AK1=0.54+15.44*(T1**(-0.2))*(1.+0.00757*ETA)
      FLASHW=(AK1-AK2)*WEIGH/100.
      WTOT=WEIGH+FLASHW
      PRINT 65,WEIGH,FLASHW,WTOT
      DTOT=DCYL+2.*FWIDTH
      AREA=PI*DTOT**2/4.
      PRINT 66,AREA

  911 FORMAT(40H PERIMETER,SURFACE,VOLUME,R OF C.GRAVITY)
   62 FORMAT(27H SHAPE DIFFICULTY FACTOR IS,3F15.5)
   63 FORMAT(32H FORGING WEIGHT WITHOUT FLASH IS,3F15.5)
   64 FORMAT(44H FLASH THICKNESS,FLASH WIDTH,FLASH RATIO ARE,3F15.5)
   65 FORMAT(41H FORGING WEIGHT,FLASH WEIGHT,TOTAL WEIGHT,3F15.5)
   66 FORMAT (38H THE PROJECTED AREA INCLUDING FLASH IS,F15.5)
   67 FORMAT(11H PERIMETER=,F15.5,9H SURFACE=,F15.5//,8H VOLUME=,F15.5,2
     15H RADIUS OF C. OF GRAVITY=,F15.5)
   28 FORMAT(19H MATERIAL DENSITY =,F10.4,17H STOCK DIAMETER =,F10.4,/19
     1H LARGEST DIAMETER =,F10.4,/10H HEIGHTS =,3F10.4)
   27 FORMAT(27H ANGLES BETWEEN CORNERS ARE)
   29 FORMAT(18H FILLET RADII ARE )
   25 FORMAT(36H AXIAL DISTANCES BETWEEN CORNERS ARE)
   24 FORMAT(25H RADII OF THE CORNERS ARE)
   22 FORMAT(18H NUMBER OF CORNERS,2I15)
   86 FORMAT(92H INPUT DATA,2ND NUMBER CORNER RADII,AXIAL DISTANCE BETWE
     1EN CORNERS,FILLET RADII,DRAFT ANGLES)
   23 FORMAT(8F10.4)
  133 FORMAT(/I5,8F12.3)
   21 FORMAT(8I10)
   82 FORMAT(I10,6F10.4)
      END
```

PROGRAM LENGTH INCLUDING I/O BUFFERS
004155

STATEMENT FUNCTION REFERENCES

LOCATION	GEN TAG	SYM TAG	REFERENCES

STATEMENT NUMBER REFERENCES

LOCATION	GEN TAG	SYM TAG	REFERENCES					
001647	C00214	21	000005	000457				
001623	C00170	22	000015	000334				
001642	C00207	23	000350	000367	000406	000425	000440	000466
001616	C00163	24	000344					
001610	C00165	25	000363					
001577	C00144	27	000421					
001562	C00127	28	000506					
001604	C00151	29	000402					
001040	L00363	31	000765	000772				
000535	L00226	32	000537					
000773	L00341	41	000543					
000720	L00314	42	NONE					
000724	L00315	43	001007					
001010	L00350	51	000650					
000662	L00304	52	001037					
001506	C00053	62	001251					
001514	C00061	63	001265					
001522	C00067	64	001335					
001531	C00076	65	001401					
001540	C00105	66	001421					
001547	C00114	67	001217					
001324	L00470	71	001311					
001333	L00473	72	001323					
001111	L00043	81	000100					
001651	C00216	82	000037	000057	000115	000135	000162	000202
000234	L00075	83	000240	000256				
000334	L00132	84	000223					
000320	L00125	85	000301	000302	000307	000317		
001627	C00174	86	000032					
001644	C00211	133	001045	001067	001117			
001500	C00045	911	001213	001244	001247			

BLOCK NAMES AND LENGTHS
- 001751

VARIABLE REFERENCES

LOCATION	GEN TAG	SYM TAG	REFERENCES		
002062	V00123	AK1	001374	001374	
002061	V00122	AK2	001363		
000311C01	A00003	ALFA	000111	000234	
002045	V00106	ALFS	001244	001247	001256